Results from the ISSI Workshop: “From the Outer Heliosphere to the Local Bubble: Comparison of New Observations with Theory”

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Workshop of the International Space Science Institute (ISSI)

From the Outer Heliosphere to the Local Bubble: Comparison of New Observations with Theory

Bern, Switzerland, 15-19 October 2007

Convenors:

Jeffrey Linsky (Chair), Univ. of Colorado, Boulder, CO, USA
Dieter Breitschwerdt, Univ. of Vienna, Austria
Priscilla Frisch, Univ. of Chicago, IL, USA
Vlad Izmodenov, Moscow State Univ., Russia
Eberhard Möbius, Univ. of New Hampshire, Durham, NH, USA
Rudolf von Steiger, ISSI, Bern, Switzerland

Local organisation:

Brigitte Fasler and Andrea Fischer, ISSI

Motivation for the October 15-19, 2007 Workshop at the International Space Science Institute (ISSI) in Bern Switzerland

- Recent space observations (e.g., Voyager, SoHO/Swan, HST/STIS, Ulysses/SWICS, ACE, etc.) have provided important new data on the outer heliosphere and ISM near the Sun.
- Major developments in theory (interaction of inflowing ISM with solar wind, MHD models of heliosphere and ISM, photoionization chemical models, etc.) provide new understanding of phenomena.
- Nearby ISM can be studied remotely by absorption line spectroscopy and *in situ* by spacecraft.
- Studies of the outer heliosphere and local ISM are now unified. (Cross-fertilization is working.)
- New terminology: circum-heliospheric interstellar medium (CHISM) refers to the ISM close to the Sun.

Seven basic questions

- What are the dominant physical processes in the termination shock and heliosheath?
- What are the three-dimensional shape and structure of the dynamic heliosphere?
- How are the interstellar plasmas and dust located inside and outside of the heliosphere related?
- What are the origin and physical properties of the very local ISM?
- What are the energy and pressure equilibria in the Local Bubble?
- What are the important physical processes in the multiphase ISM located inside the Local Bubble?
- What are the roles that magnetic fields play in the outer heliosphere and Local Bubble?

What are the dominant physical processes in the termination shock and inner heliosheath?

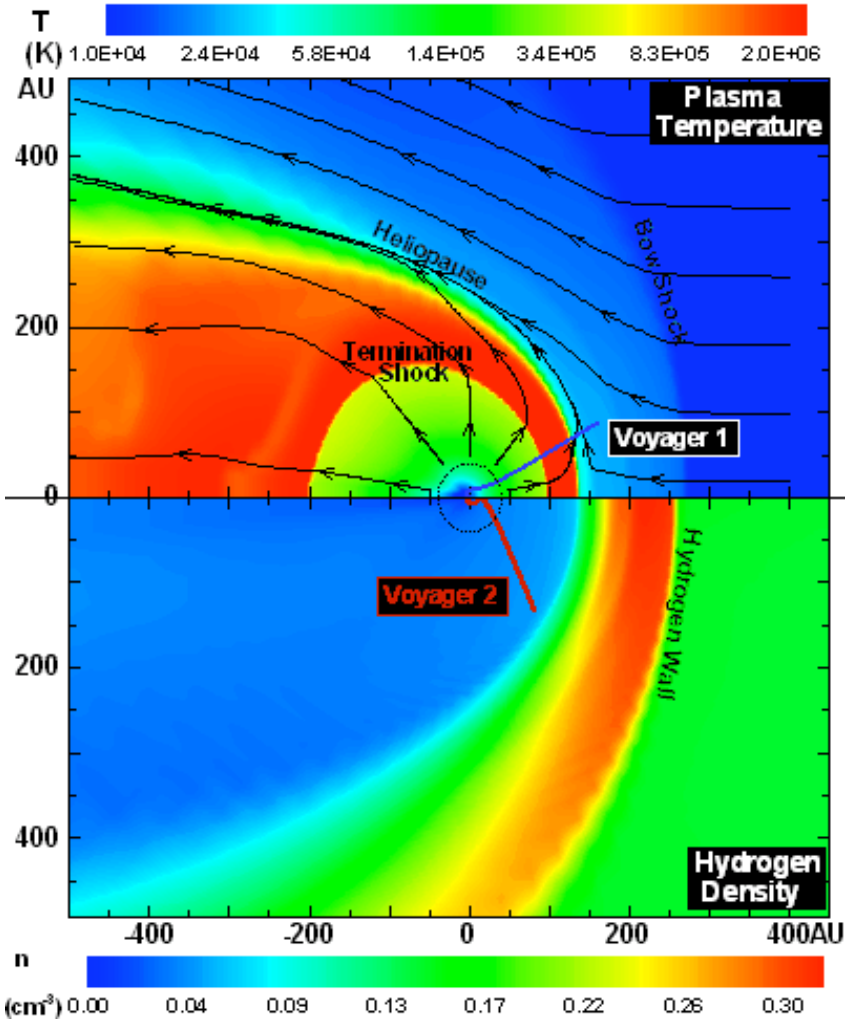
(J. Richardson, R. Jokipii, A. Balogh, V. Florinski, D. McComas)

- Shock physics: weak shock ($r=2.6^{+0.4}_{-0.2}$) inferred from properties of plasma before and after TS crossing as measured by Voyagers 1 and 2. TS width ~0.2 AU.
- Charge exchange between incoming IS neutral H and solar wind protons → energetic neutral atoms (ENAs) and pick-up ions.
- Inflowing neutral H slows the solar wind speed.
- IS magnetic field moves the TS inward, makes the nose blunt and the shape asymmetric.
- Co-rotating interacting regions (CIRs) compress and strengthen magnetic field in the solar wind.

Termination shock jump conditions

Which Voya-ger	When (mo/yr)	Where (AU)	T+/T-	n+/n-	v+/v-	B+/B-	Shock speed (km/s)
V1	Dec. 2004	94.0			0.4	3.05	-100
V2	Aug. 2007	84	20	2	1/2		

Interaction of Stars with their LISM



Müller (2004)

Heliosphere is the structure caused by the momentum balance (ρv^2) between the outward moving solar wind and the surrounding interstellar medium.

Magnetized solar wind extends out to heliopause, diverts plasma around Solar System, and modulates the cosmic ray flux into Solar System.

Most neutrals stream in unperturbed, except neutral hydrogen, which due to charge exchange reactions, is heated and ***decelerated*** forming "Hydrogen Wall" (log N_H (cm^{-2}) ~ 14.5).

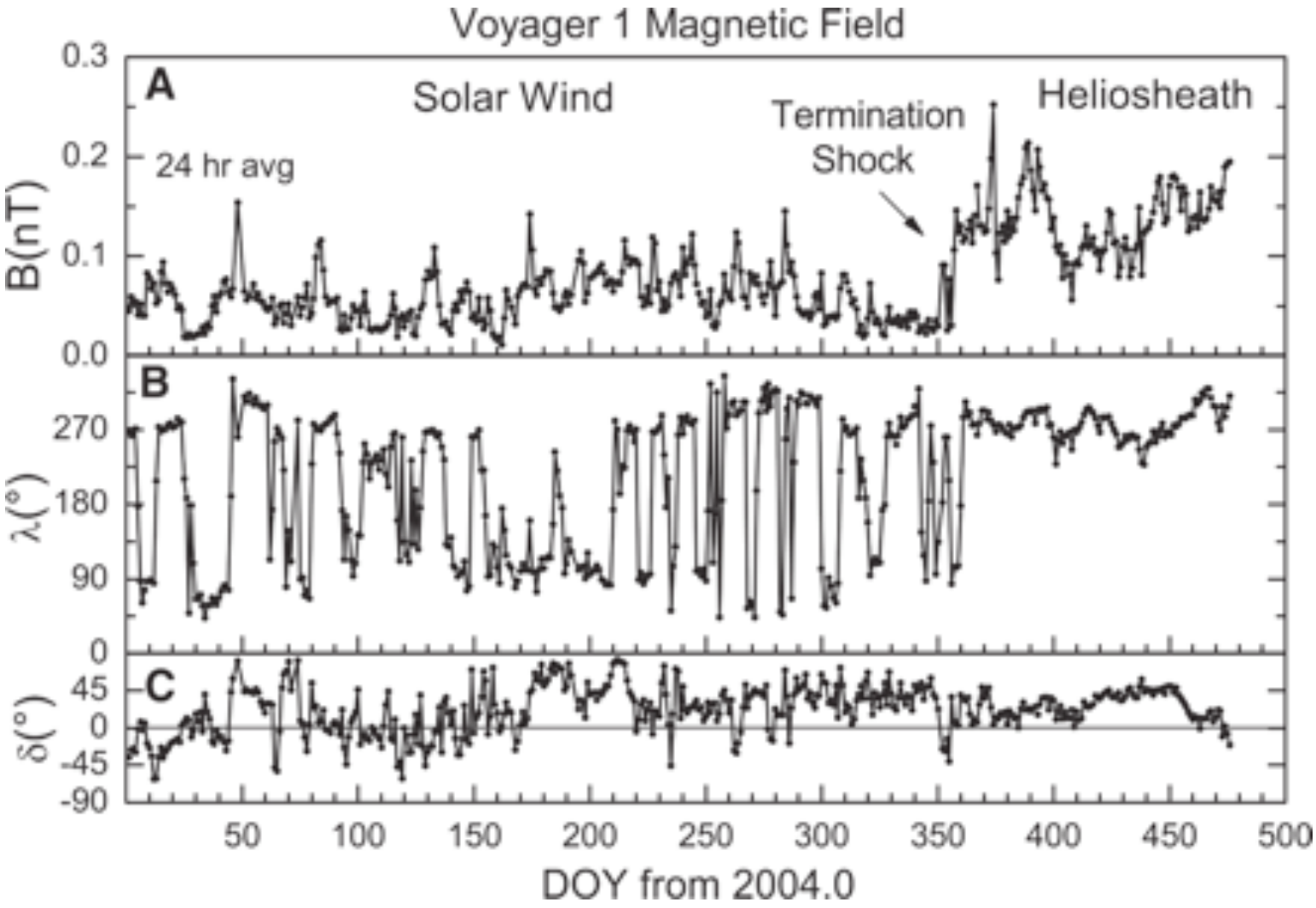
Reviews of heliospheric modeling: Wood (2004), Zank (1999), and Baranov (1990).

Reviews of interaction of LISM with heliosphere: "Solar Journey" Frisch (2006), and Redfield (2006)

What has Voyager 1 told us about the Termination Shock?

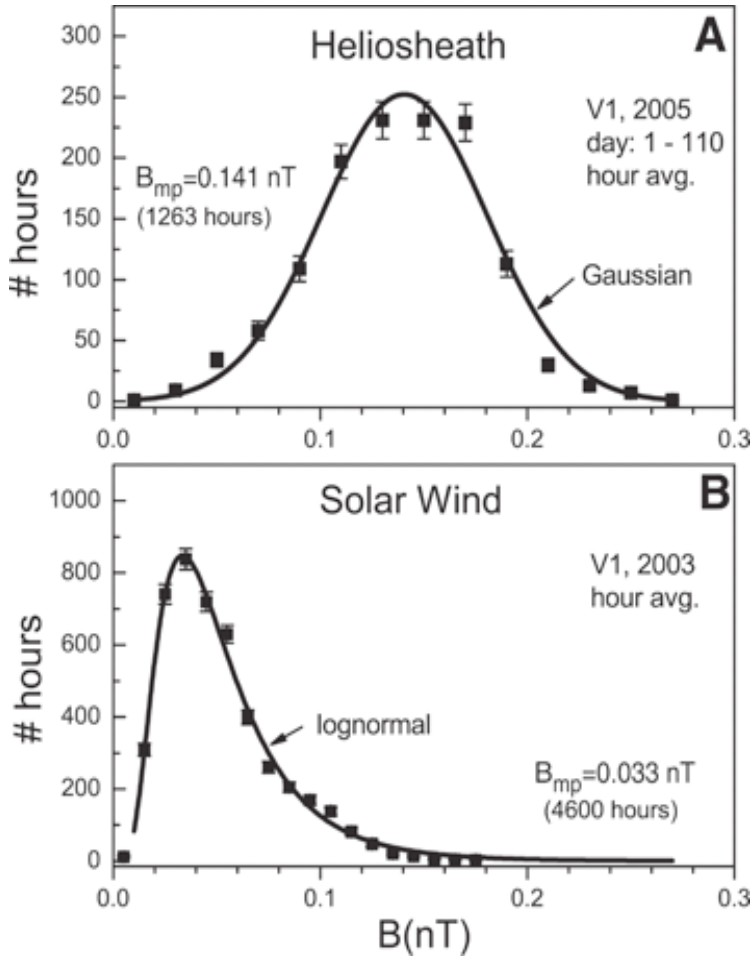
- Voyager 1 was launched 5 Sept 1977, passed Jupiter and Saturn and crossed the termination shock (TS) on 16 Dec 2004 at 94 AU from the Sun.
- Onboard detectors measured the magnetic field and energies and directions of energetic electrons, protons, and He nuclei.
- Weak shock: velocity jump (r=2.6).
- TS not spherical due to magnetic field and also mass loading by IS neutral H atoms.
- TS moves in and out with the solar cycle.
- Solar wind in heliosheath slower, hotter, and denser than inside the TS.
- The TS was expected to be the location where anomalous cosmic rays (ACRs) are accelerated, but peak in ACR flux not at the TS.

Change in Magnetic Field Strength and Direction (heliographic) at the TS: Burlaga (2005) Science 309, 2027



Change in Magnetic Field at the TS: Burlaga et al. (2005)

- Magnetic compression ratio across TS: 3+/-1.
- Complete change in average field strength perhaps due to thermalization of the plasma by the TS.
- Inward moving TS (>90 km/s) may have crossed Voyager 1: Jokipii (2005) ApJ 631, L163.
- 1nT=10μG

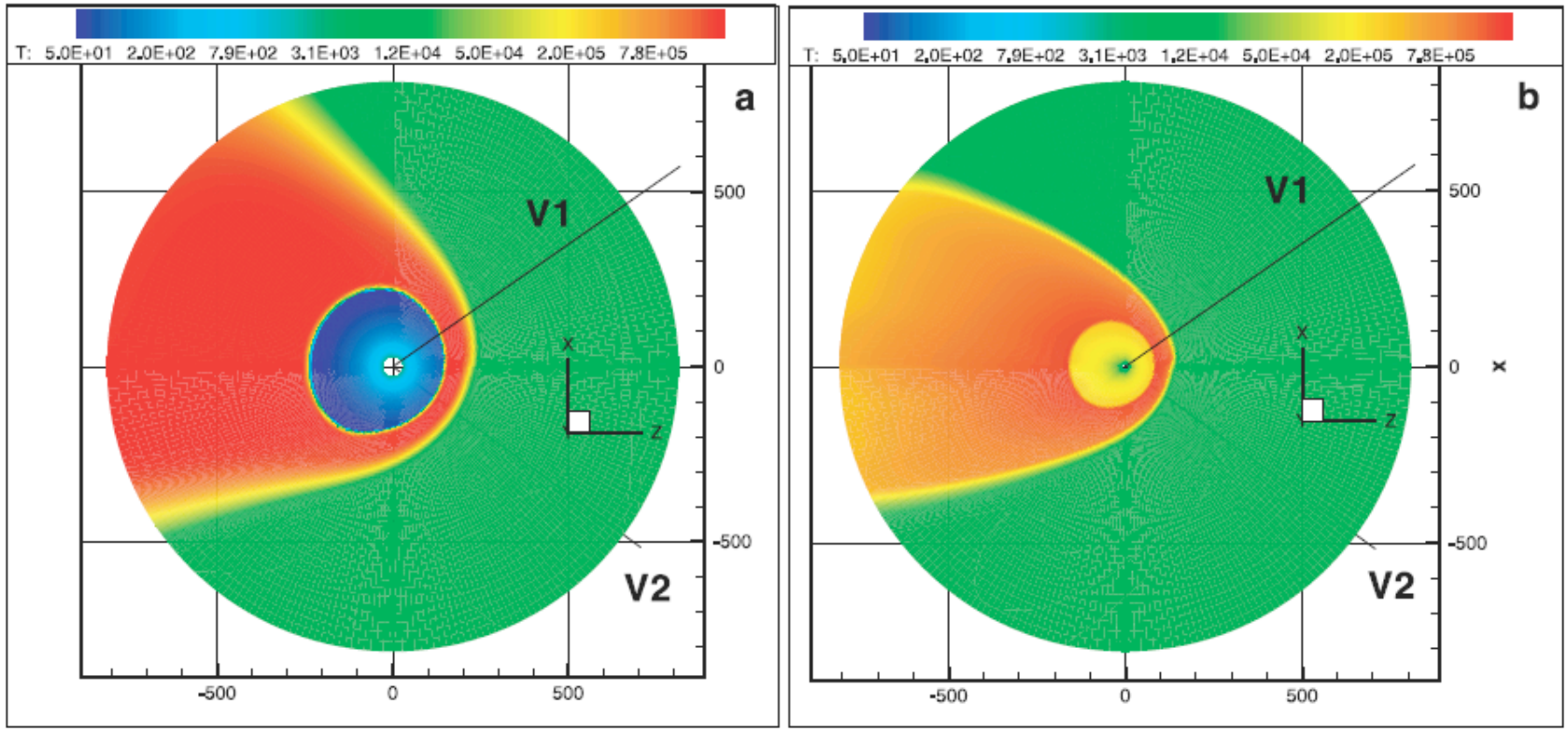


What are the three-dimensional shape and structure of the dynamic heliosphere?

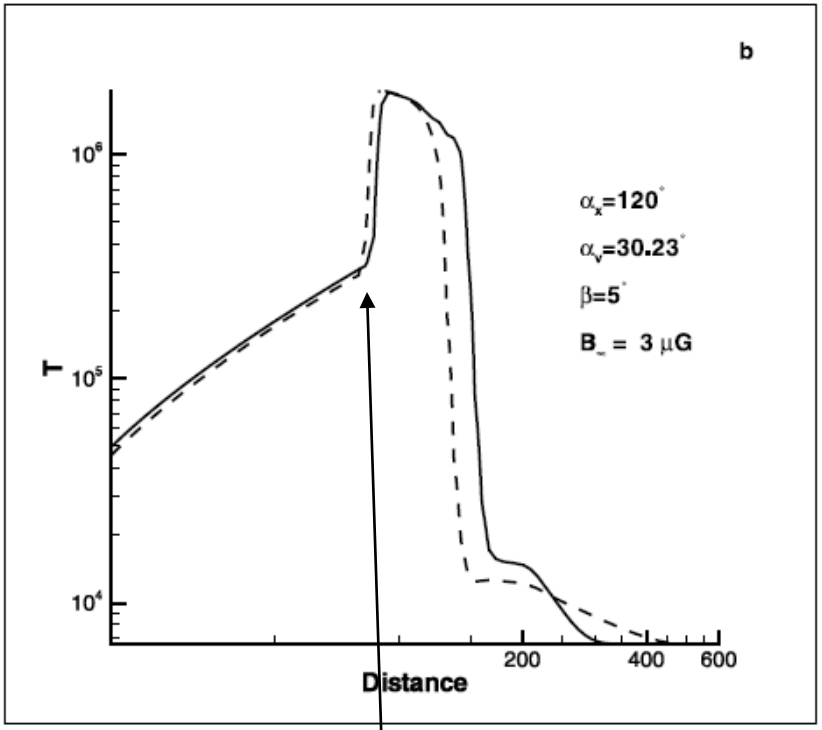
(E. Stone, B. Wood, N. Pogorelov)

- Evidence for TS asymmetry about node direction: Very different crossing distances (94 AU for V1, 84 AU for V2).
- Asymmetry of TS due to IS magnetic field.
- Asymmetry reduced by neutral H atoms that charge exchange with solar wind ions.

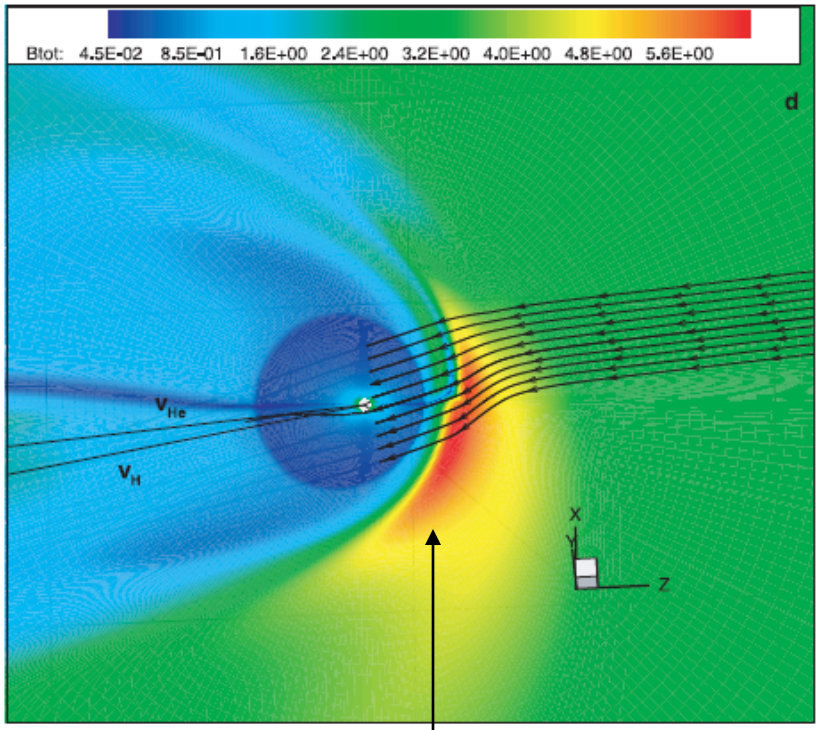
Effect of inflowing neutral H atoms (with charge exchange) on the asymmetry of the TS and bow shock. Left: ideal MHD; Right: including neutrals (Pogorelov et al. ApJ 668, 661 (2007)). B_∞=2.5μG tilted 45° to ecliptic plane.



Left: model T distribution along V1 path (solid) and V2 path (dashed) for 120° of B_∞ vs V_∞.
Right: B_{tot} (μG) and neutral H streamlines
(Pogorelov et al. ApJ 668, 661 (2007))



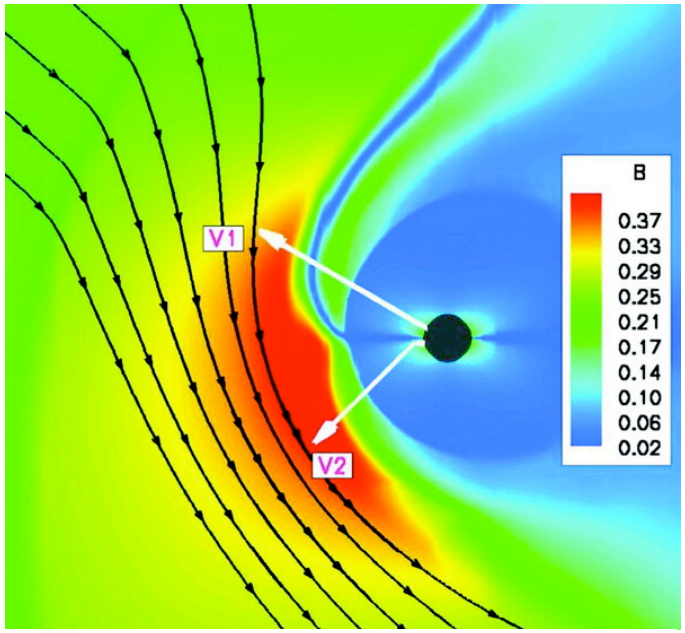
Termination shock

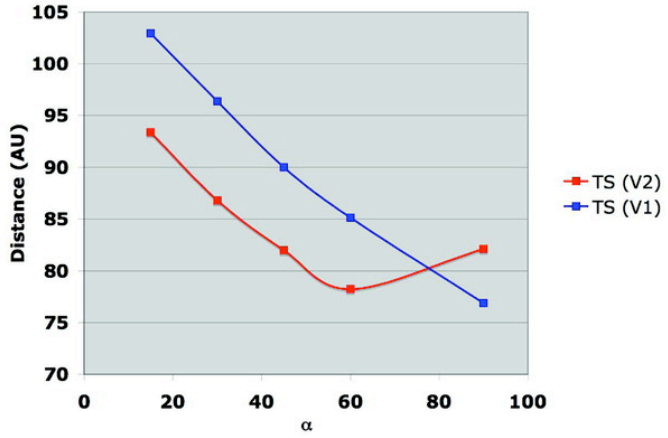


Hydrogen wall

Effect of the Interstellar Magnetic Field on the Heliosphere (Opher et al. 2006, 2007)

- 3-D MHD adaptive grid models (BATS-R-US code) with interstellar magnetic field (B~1.8μG) α=30-60 degrees from inflow direction. (60-90 degrees from Galactic plane).
- v_{SW}=450 km/s, v_{ism}=25.5 km/s Parker spiral B=2μG at equator
- Produces a N-S asymmetry in the TS and heliosheath and a deflection in the current sheet (blue).
- TS moved in 2.0 AU for Voyager 1 with TSP streaming outward from Sun along a spiral field line that does not first go through the TS.
- Moves TS inward more in S (Voyager 2) than N (Voyager 1).
- Where Voyager 2 crosses the TS will be the critical test of value of α.



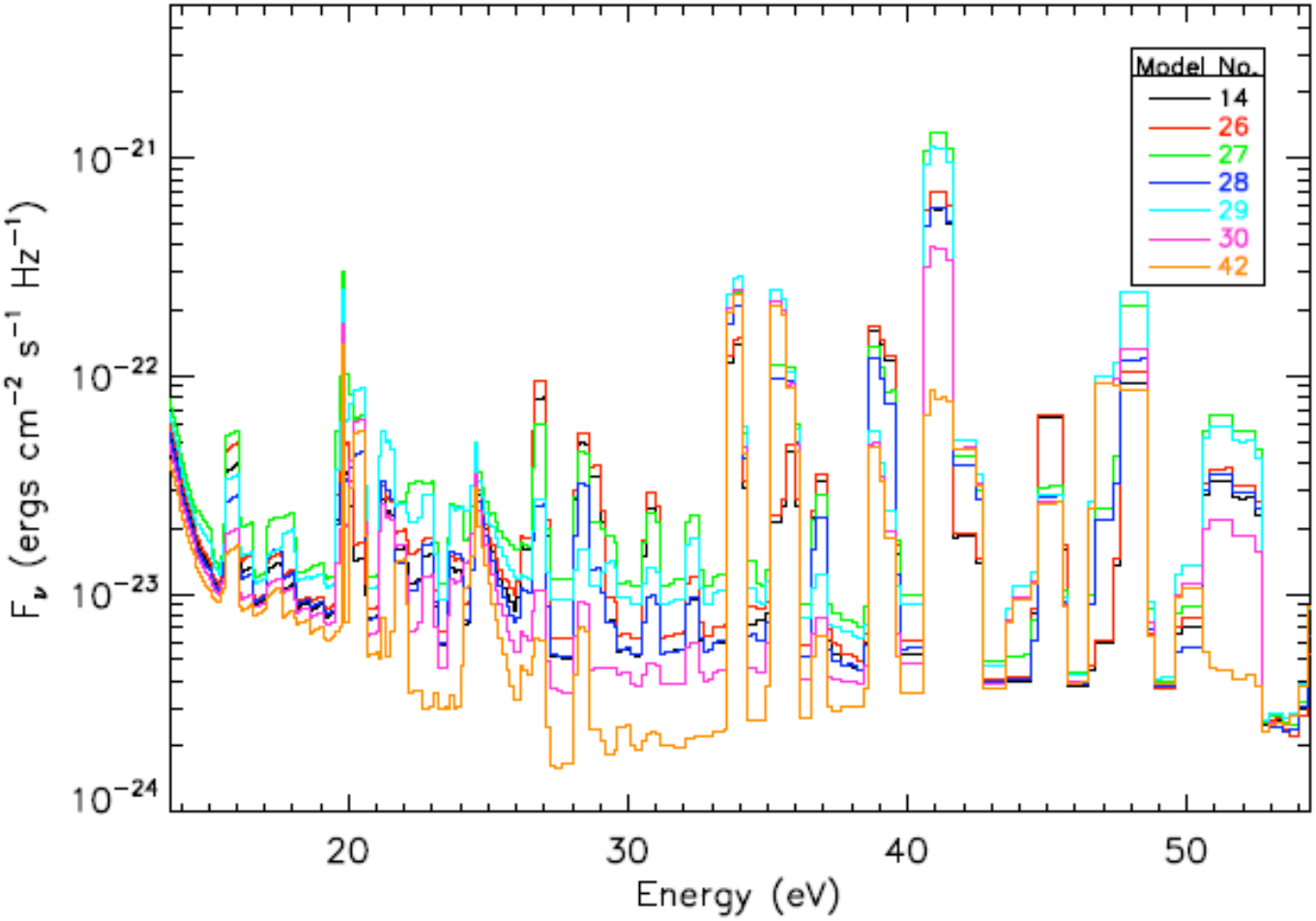


How are the interstellar plasmas and dust located inside and outside of the heliosphere related?

(P. Frisch, V. Izmodenov, E. Quémerais, G. Gloeckler, M. Bzowski)

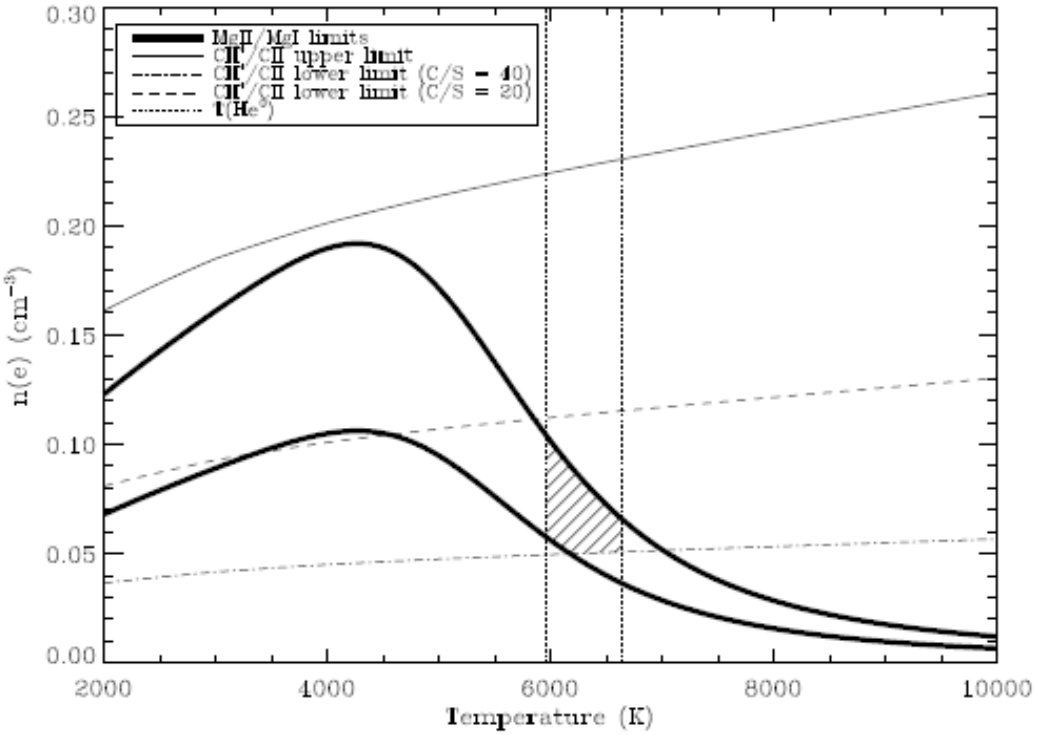
- n(HI) = 0.110±0.008 in heliosheath.
- n(HI) = 0.200±0.039 extrapolated to CHISM (Circum-heliospheric interstellar medium) with Izmodenov model for filtration factor (54%).
- n(HI) = 0.19-0.20 from N(HI) to near by stars.
- Beyond 10 AU n(HI) mostly interstellar but 2/3 of incoming H atoms have been charge-exchanged
- General agreement between *in situ* plasma measurements, Lyα backscattering, and photoionization models of the ISM.
- IS dust enters heliosphere from same direction as gas. Nearly all of Mg, Si, and Fe but only 50% of C in dust grains. Why too many large grains?

Photoionization models of the CHISM including UV radiation from hot stars and EUV and X-rays from Local Bubble and cloud interfaces (Slavin & Frisch)



Ionization in the CHISM (Slavin)

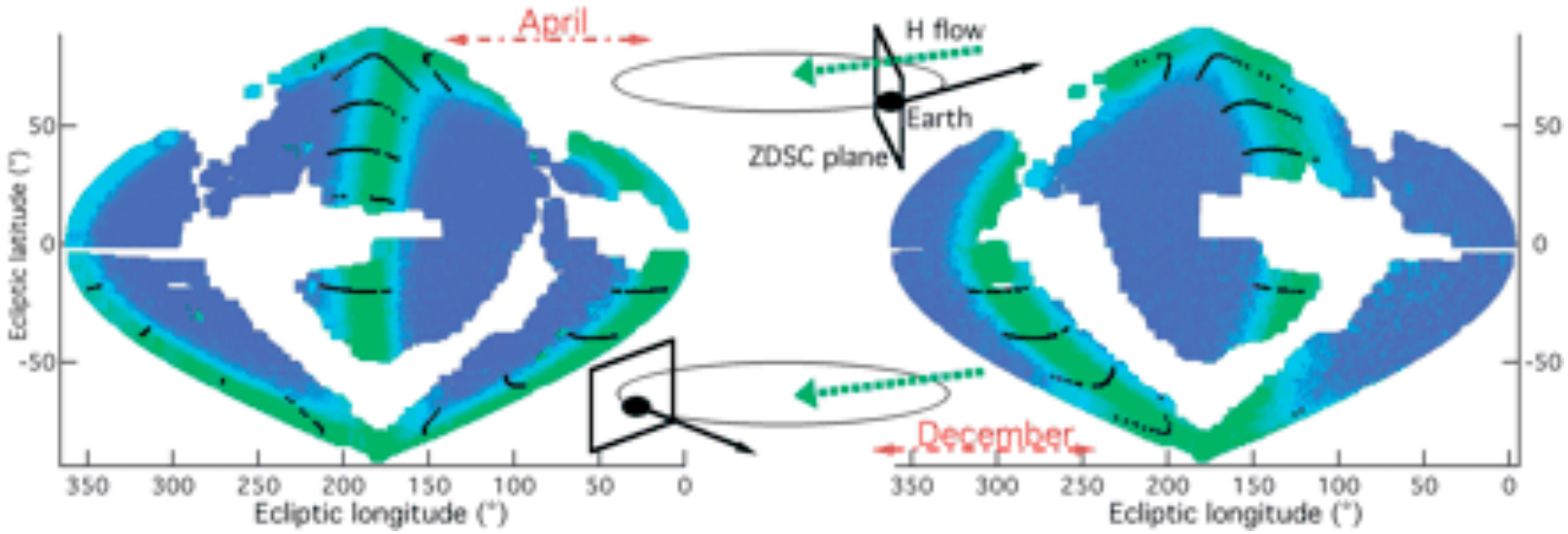
- Measure n_e from ratios of MgII/MgI and CII*/CII (1335Å/ 1334Å).
- H 22% ionized
- He 43% ionized
- In solar wind electrons are supermaxwellian (energetic tails). May be similar in CHISM?
- In solar wind P_{pickup}/P_{total}=0.75. Could this be similar in CHISM?



New result from Redfield and Falcon (submitted) that for 7 lines of sight with LIC velocity, CII*/CII → n_e=0.12±0.4 cm^{-3}

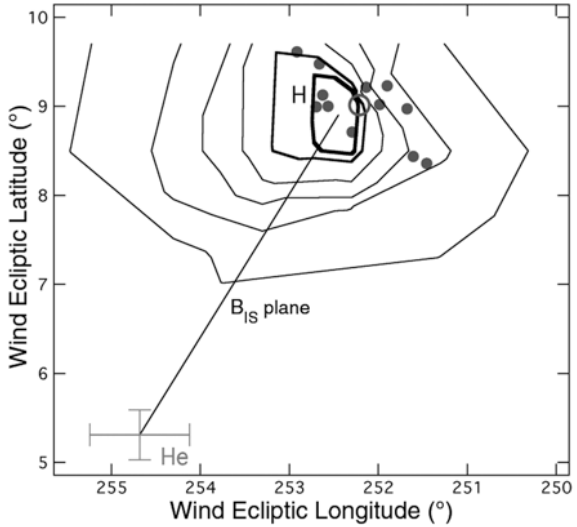
SWAN maps Backscattered Lyman-α Radiation from Neutral Hydrogen Flowing into the Heliosphere using a Hydrogen Gas Absorption Cell Spectrometer

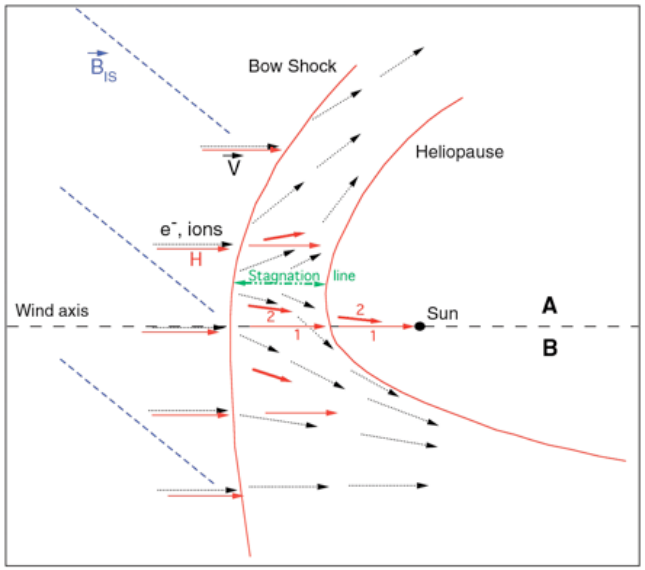
- Maximum in the Lyman-α sky glow when inflowing H has maximum Doppler shift relative to SOHO.
- Maps show Lyman-α glow at different times of year when SOHO has different velocities relative to the H inflow vector.



Deflection of Neutral H vs. He due to charge exchanged Solar Wind Protons becoming H Secondaries

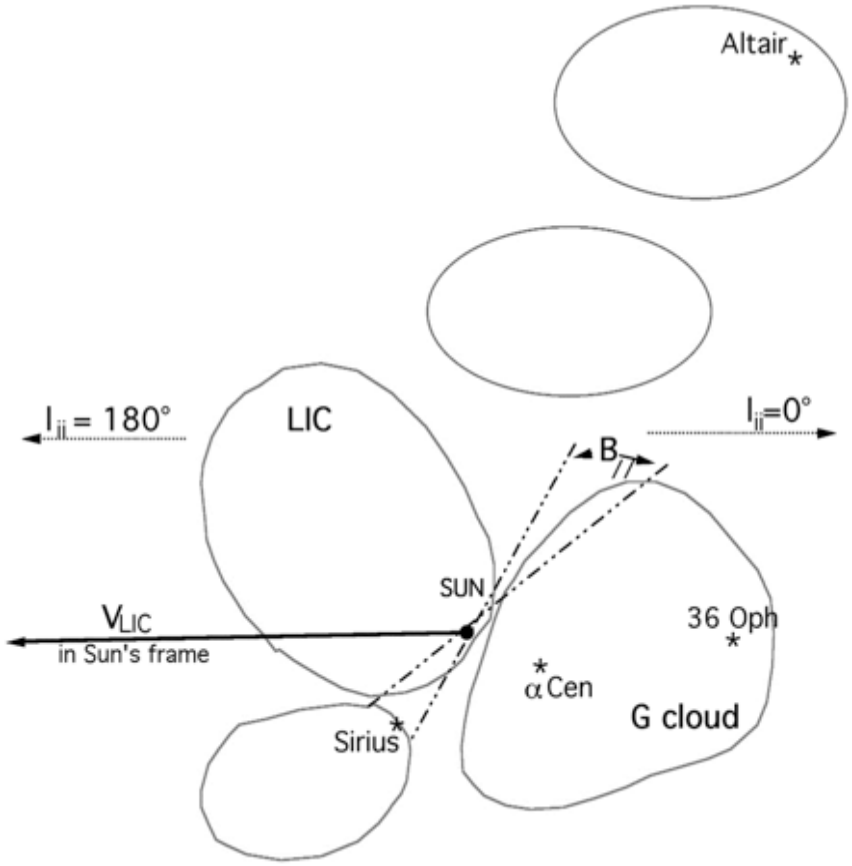
- Incoming He atoms retain the ISM inflow direction because no charge exchange.
- H secondaries will be deviated only if the interstellar magnetic field is inclined relative to the gas flow direction.
- Measured deviation is 4+/-1 degrees.
- Izmodenov et al. (2005) models with B_∞=2.5μG at 45° from gas inflow direction predict TS (V1) at 94 AU and HI-HeI deflection angle of 2°-3°.





Inferring the Direction of the Local Interstellar Magnetic Field

- MHD models consistent with the deviation of H relative to He predict the magnetic field direction in Galactic coordinates (40-60 degrees from Galactic plane).
- Magnetic field is parallel to the edges of the LIC and G clouds and likely compressed by the relative motion of the two clouds.
- Consistent with inferred direction of magnetic field in disk (46°±20° from NGP).



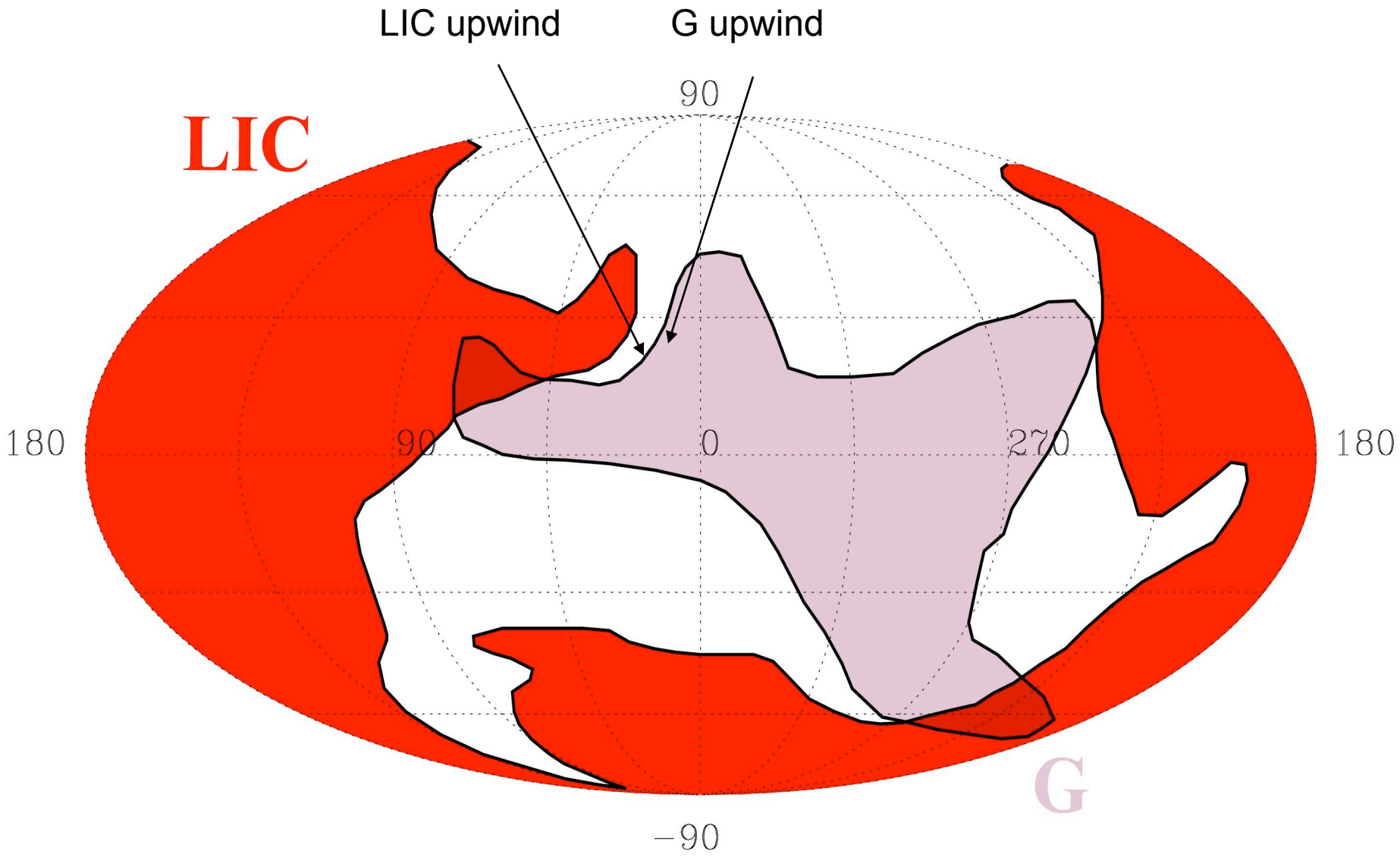
What are the origin and physical properties of the very local ISM?

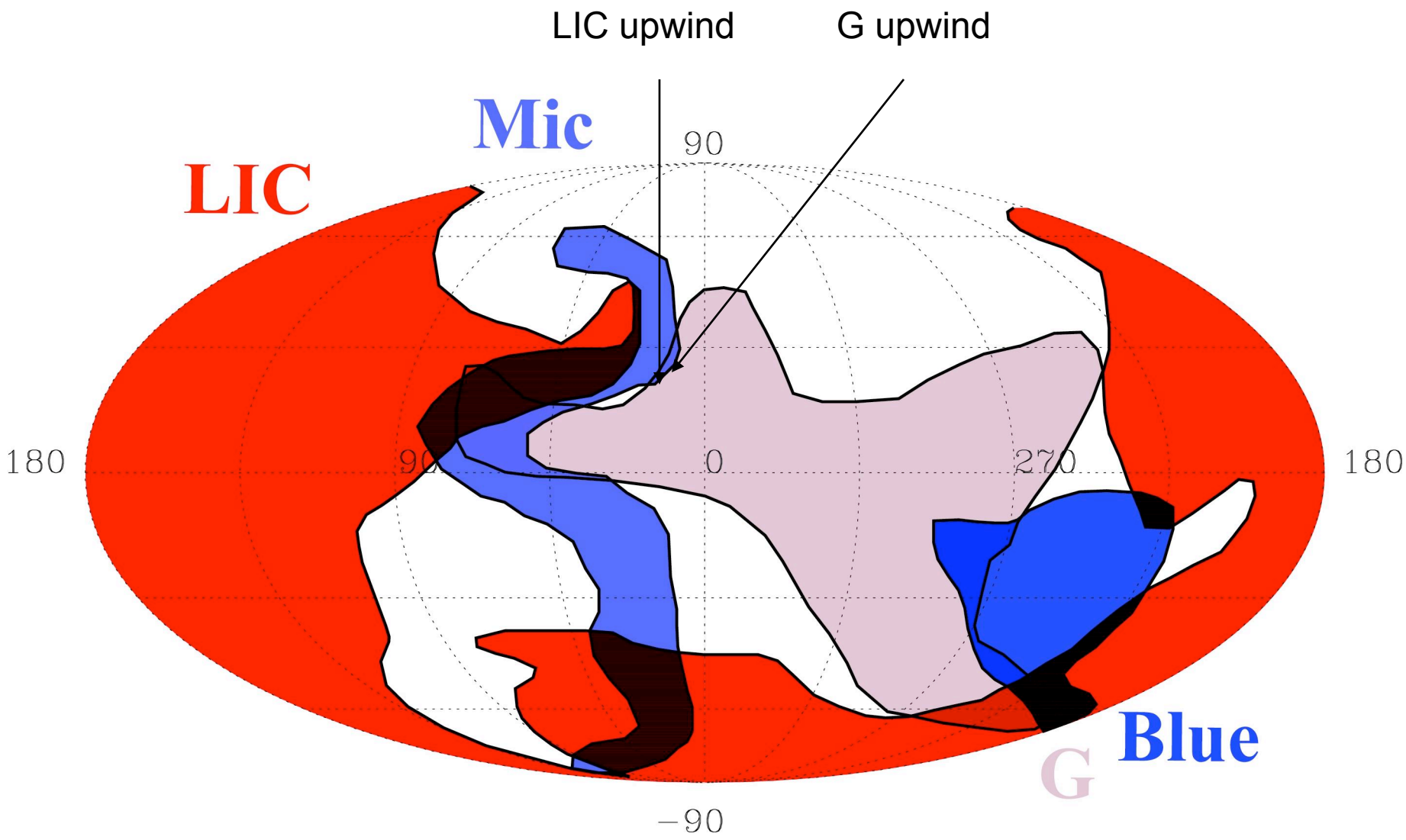
(J. Slavin, S. Redfield, H. Krüger, B. Draine)

- Photoionization models of CHISM can explain most of ionization, depletion, abundance data (Slavin) but energy balance an issue (Shocked plasma?, Are there missing heating terms?)
- Detailed kinematic model of warm gas clouds in the CHISM (Redfield & Linsky).
- The Sun is likely in a transition zone between LIC and G Clouds.
- Clouds can interact→turbulent, ionized edges that can explain scintillation of quasars.

Is the Sun located inside the LIC or the G Cloud?
(Redfield & Linsky ApJ 673, 283 (2008))

Parameter	Interstellar He atoms inside the heliosphere	LIC	G Cloud
V (km/s) (upwind)	26.24±0.45 (Möbius et al. 2004)	23.84±0.90 (79 LOS)	29.6±1.1 (21 LOS)
T (K)	6300±390 (Möbius et al. 2004)	7500±1300 (19 LOS)	5500±400 (5 LOS)


LIC upwind
G upwind
LIC
90
180
90
0
270
180
G
−90


LIC upwind
G upwind
Mic
LIC
90
180
90
0
270
180
−90
G
Blue

Effect of the Interstellar Magnetic Field on the Heliosphere (Opher et al. 2006, 2007)

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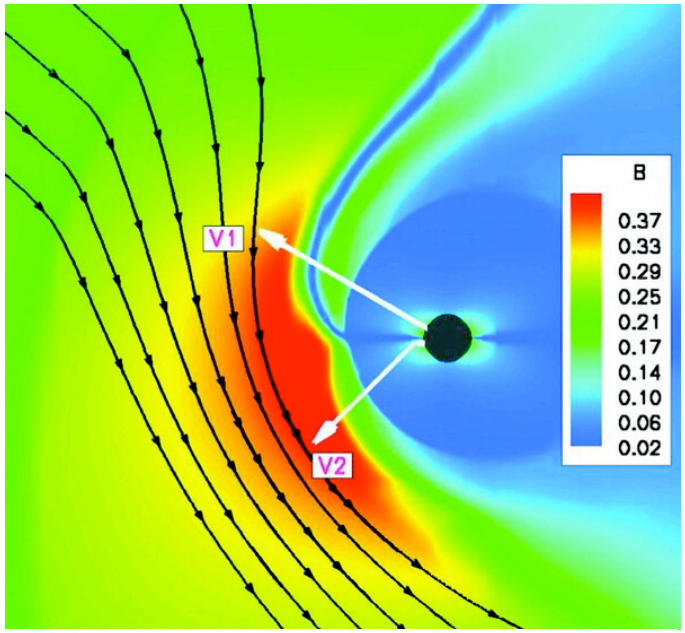
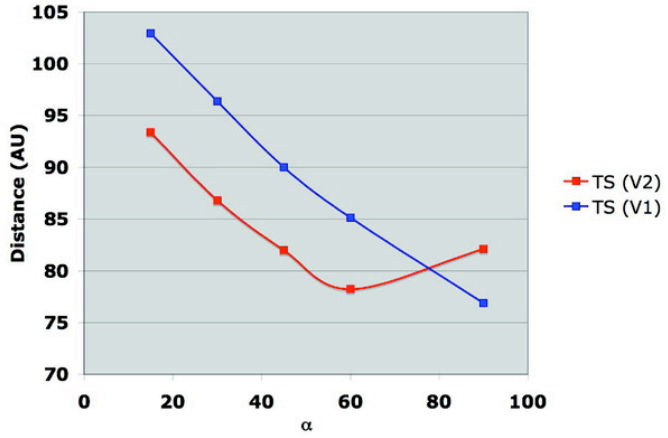
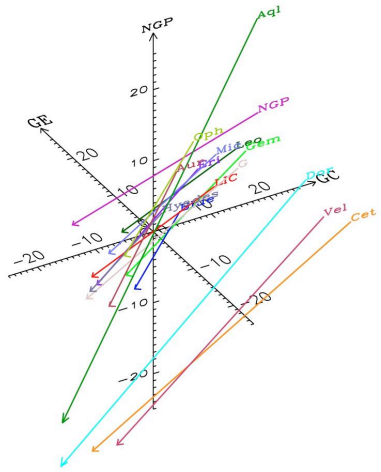
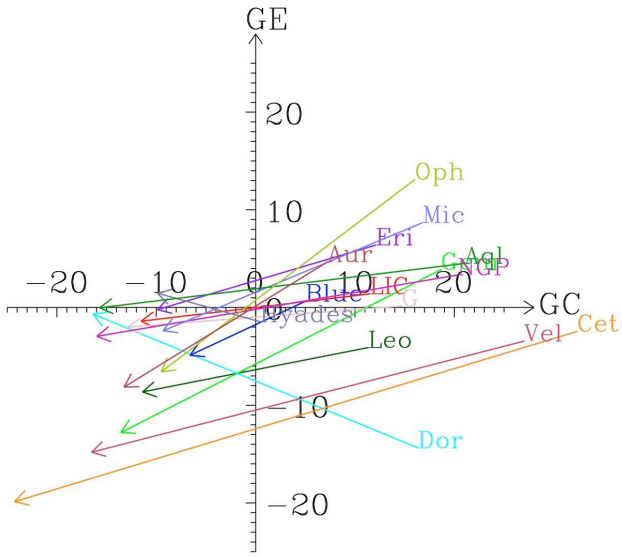
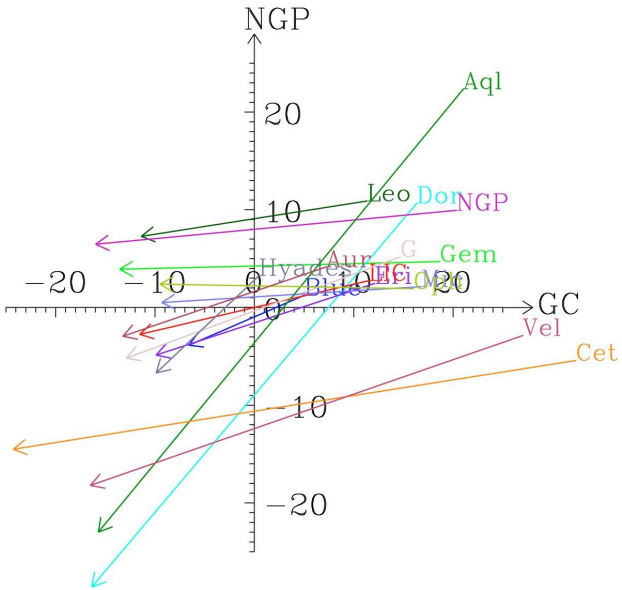


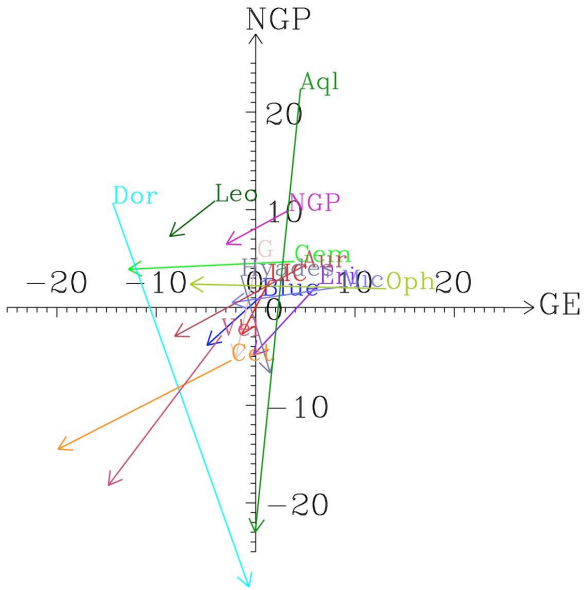


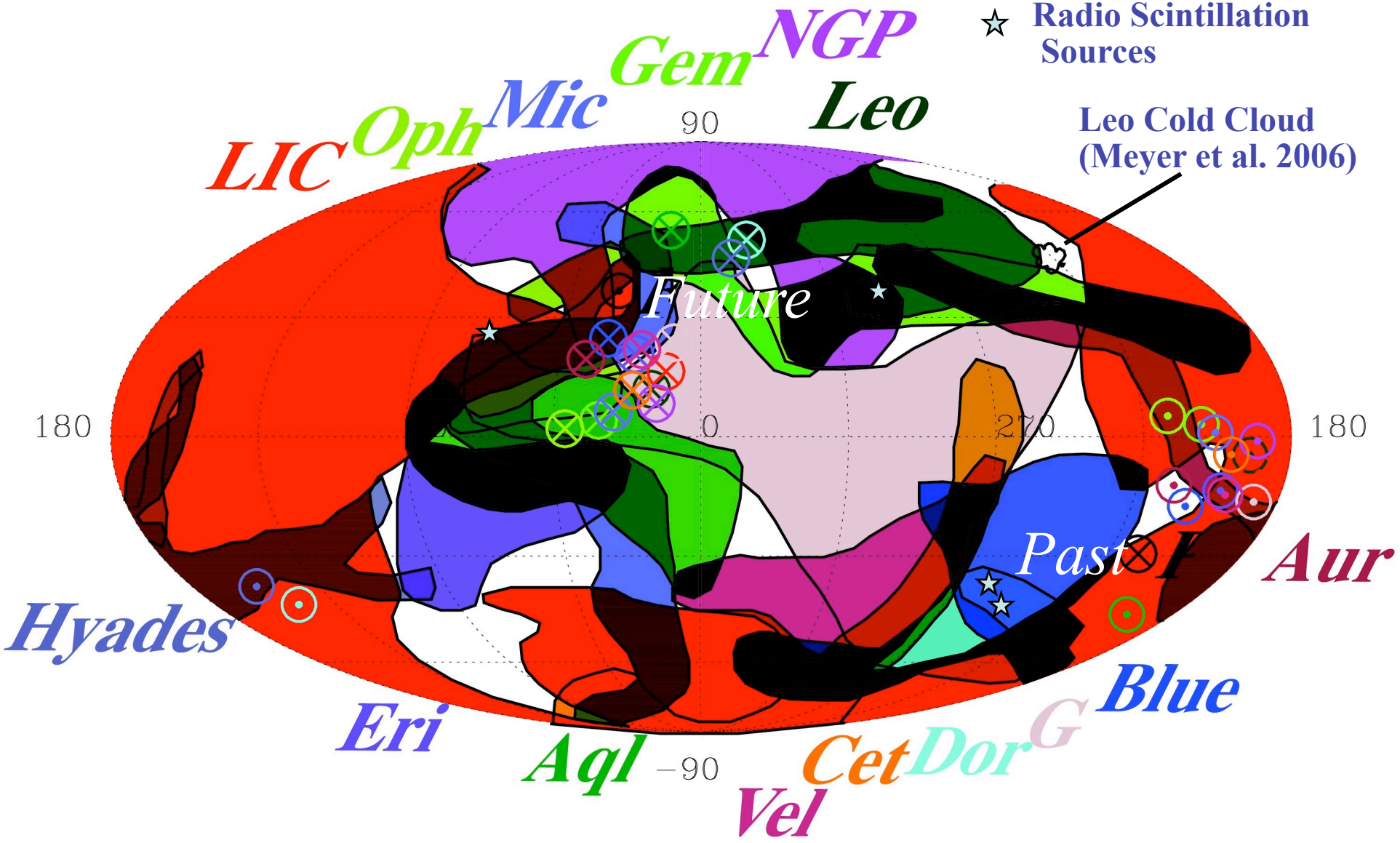
Heliocentric Vector Solutions



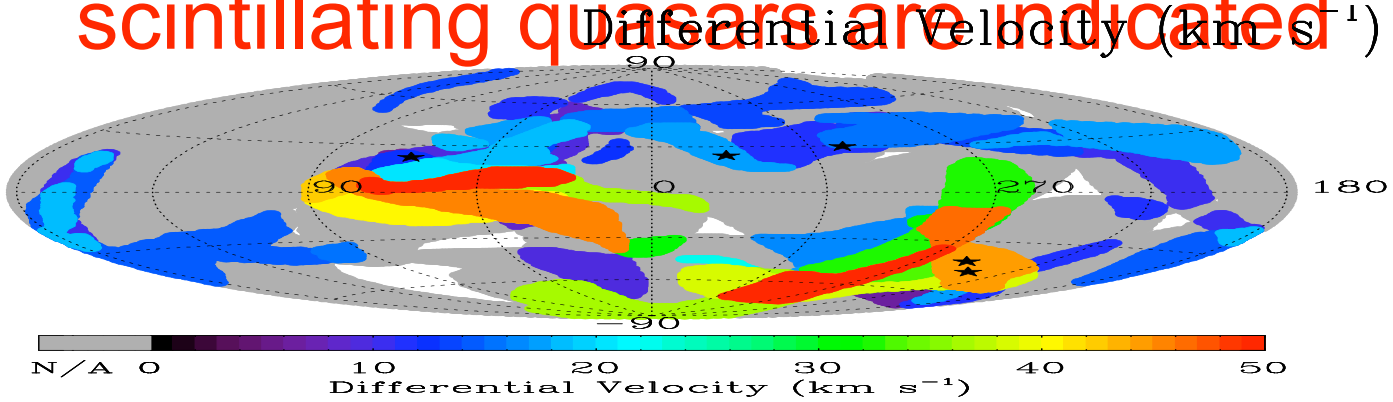







Radio Scintillation Sources
Leo Cold Cloud (Meyer et al. 2006)
NGP
Gem
Mic
Oph
LIC
Leo
90
Future
180
0
270
180
Past
Aur
Hyades
Blue
Eri
Aql
−90
Cet
Dor
G
Vel

Differential velocity between LISM clouds along same line of sight. Large amplitude scintillating quasars are indicated



What are the energy and pressure equilibria in the Local Bubble?

(E. Jenkins, D. Koutroumpa, R. Shelton, B. Welsh)

- Classical models of ISM in hydrostatic equilibrium cannot explain the observed gas pressure disequilibrium.
- Does the Local Bubble contain hot gas ($T \approx 10^6$ K), or is the soft X-ray emission all (or mostly) SWCX in the heliosphere? If yes, then perhaps the LB is warm ($T \approx 40{,}000$ K) and gas far out of ionization equilibrium (Breitschwerdt et al. 2001). CHIPS upper limits on FeXI and FUSE upper limits on OVI (Barstow and Welsh) support little hot gas.
- Could magnetic pressure balance external and internal pressure?
- MHD models of ISM are very dynamic (not HSE)

Classical Theoretical Models of the ISM

References

- Field, Goldsmith, Habing (1969) ApJ 155, L149 (CNM,WNM/WIM)
- McKee, Ostriker (1977) ApJ 218, 148 (CNM, WNM/ WIM,HIM)
- Wolfire et al.(2003) ApJ 587,278 (3-phase)
- Ferrière (2001) Rev.Mod.Phys. 73(4)1031 (ISM data)
- Cox(2005) ARAA 43, 337 (important review)

Assumptions

- Hydrostatic equilibrium (only thermal pressure included)
- Thermal equilibrium
- Heating by UV photoelectric (on gas and grains) (depends on SN rate)
- Cooling (radiation by forbidden lines, PAHs)
- Thermally unstable P(n) curve allows coexistence of 3 phases at n=0.3 to 30/cm^3, P/ k=1700-4400, T=270-5500K)
- Nonthermal pressure terms not included

Constituents of the Local Bubble: Pressure Components (K/cm³)

Weight of overlying gas: $P_{over}/k \approx 22{,}000$ (midplane)

Cosmic rays: $P_{cr}/k \approx 9300$

Magnetic pressure:

$$P_{mag}/k = B^2/8\pi k = 7200\ (B/5\mu G)^2$$

Ram pressure: $P_{ram}/k = \rho v^2/k = 2400(n_{tot}/0.3)(v/8\ km/s)^2$

Thermal pressure: $P_{th}/k = n_{tot}T \approx 2300$ (warm and cold)

(but a wide range)

$P_{th}/k = n_{tot}T \approx 15{,}000$ (hot less SXCX)

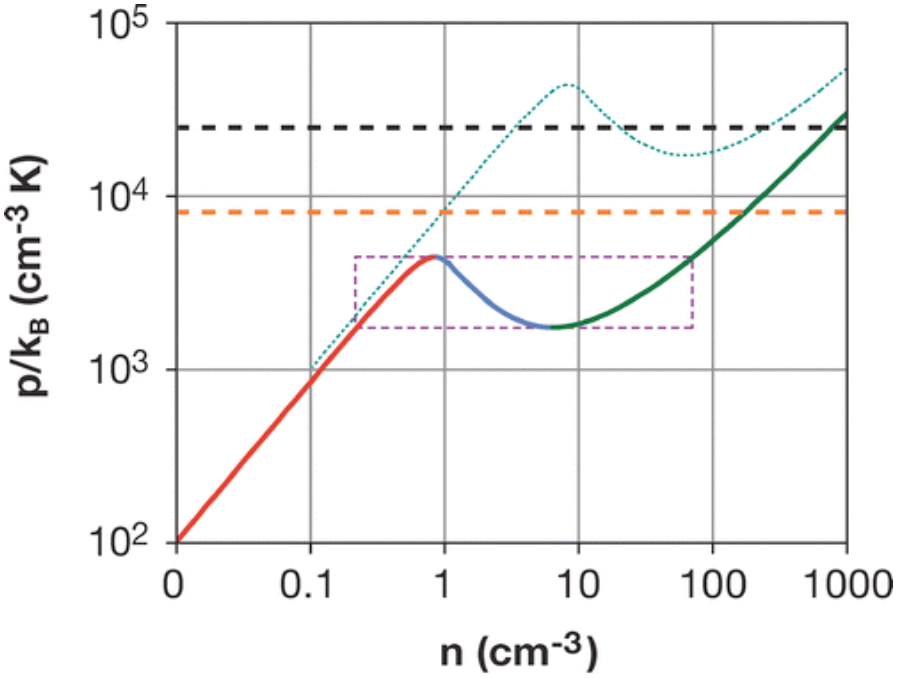
[$P_{mag}=P_{th}$ when $B=2.8\mu G$] Outside of heliosphere $B \approx 3\mu G$

[$P_{mag}=P_{over}$ when $B=8.7\mu G$] At edge of LB, polarization data imply $B=8^{+5}_{-3}\ \mu G$ (Andersson & Potter (2006)

[$P_{mag}+P_{cr}$ estimated from observed synchrotron emission]

Thermal Pressure Disequilibrium

- Theoretical two-phase equilibrium ISM model (Wolfire et al. 2003; Cox 2005).
- Blue dotted curve is 10X higher heating rate.
- Black dashed line is total midplane pressure due to overlying matter.
- Orange dashed line is mean magnetic pressure.
- Nonthermal pressure (dynamic, magnetic, cosmic ray) dominates the thermal pressure. Therefore, a wide range of pressures (1700-20,000 can be compensated by different nonthermal terms.



Cox, DP. 2005
Annu. Rev. Astron. Astrophys. 43: 337–85

Is this the whole story? Dynamic pressures can be measured by high-resolution UV spectroscopy.

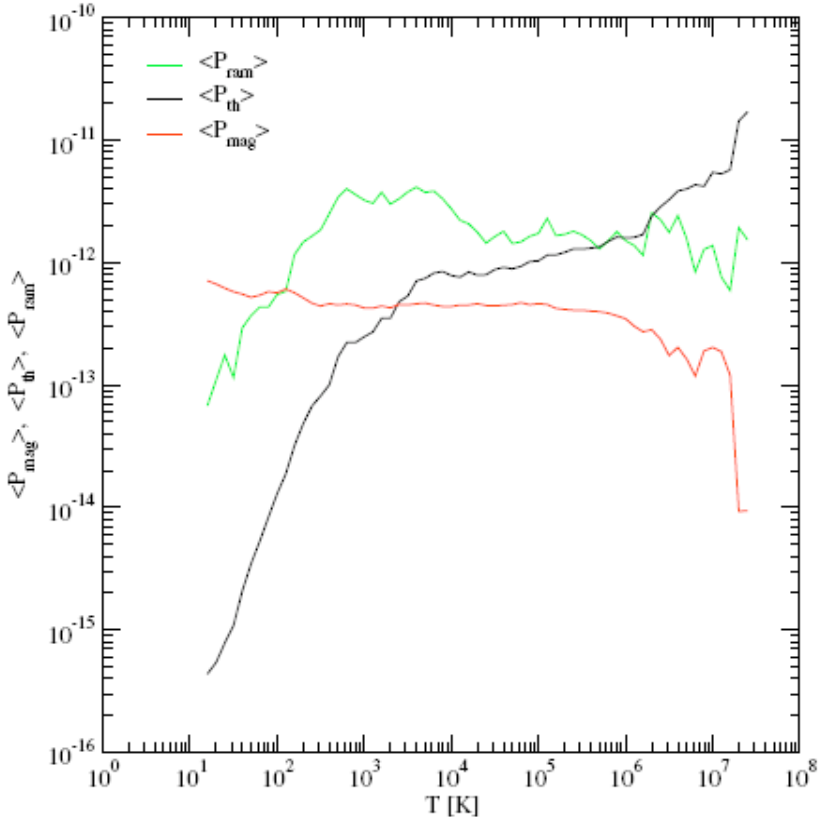
What are the important physical processes in the multiphase ISM located inside the Local Bubble?

(D. Breitschwerdt, S. Spangler, S. Snowden, S. Stanimirovic, M. de Avillez)

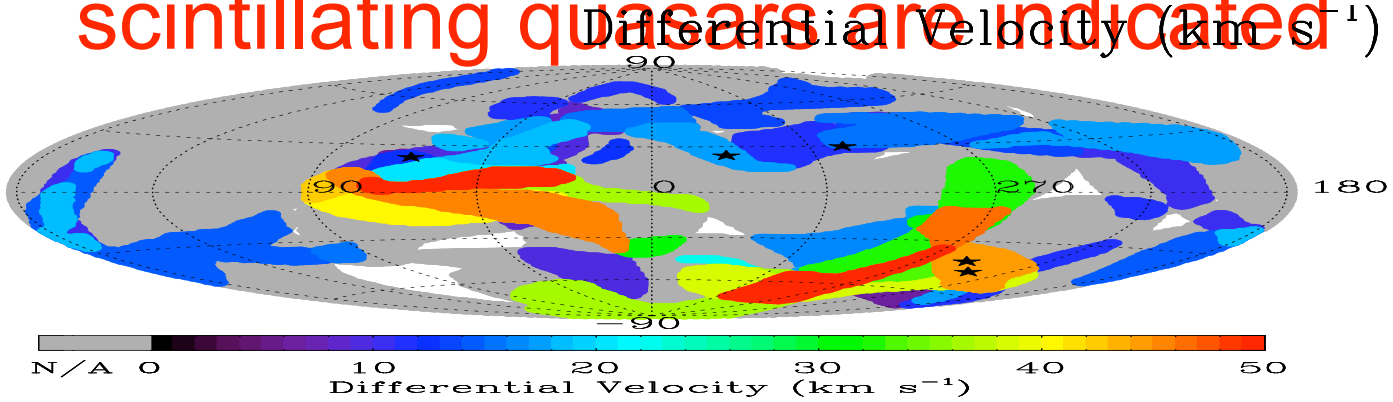
- Turbulence is very important in the ISM because the Reynolds number is large (10^5 – 10^7). Driven by SNe, stellar winds, galactic rotation, self gravity, etc.
- Nearby pulsars useful for measuring $\langle n_e \rangle \approx 0.016$ in LB.
- SWCX in heliosphere can explain all of ¾ keV and much of ¼ keV background. Is there any 10^6 K gas in the LB?
- AU-scale neutral and ionized structures exist in ISM. Detected in quasar scintillation and 21-cm and Na I line absorption toward high proper motion pulsars. Produced by collisions of warm clouds.
- Flow of gas to halo acts as a pressure relief valve in models of ISM.

3D MHD models of the ISM driven by supernovae (de Avillez & Breitschwerdt A+A 436, 585 (2005))

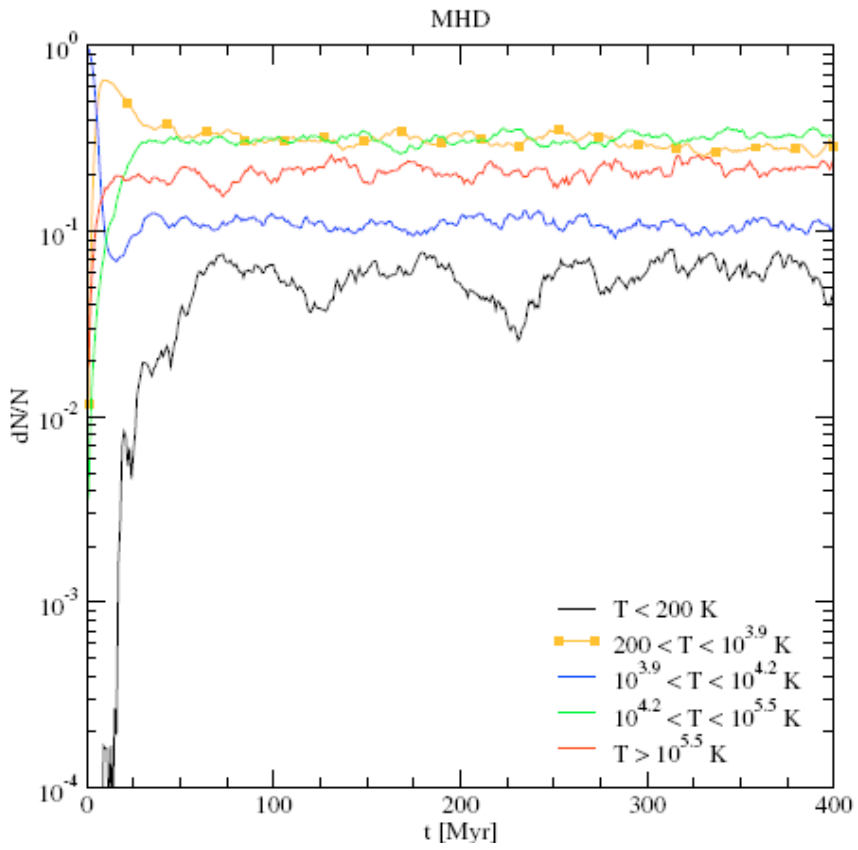
- Ram pressure dominates from 100 K to 10^6 K. Thermal pressure dominates for T>10^6 K.
- “Classical” models in thermal pressure equilibrium are not realistic.
- There is matter at all temperatures and a wide range of thermal pressures.
- Cold matter in shock compressed layers.

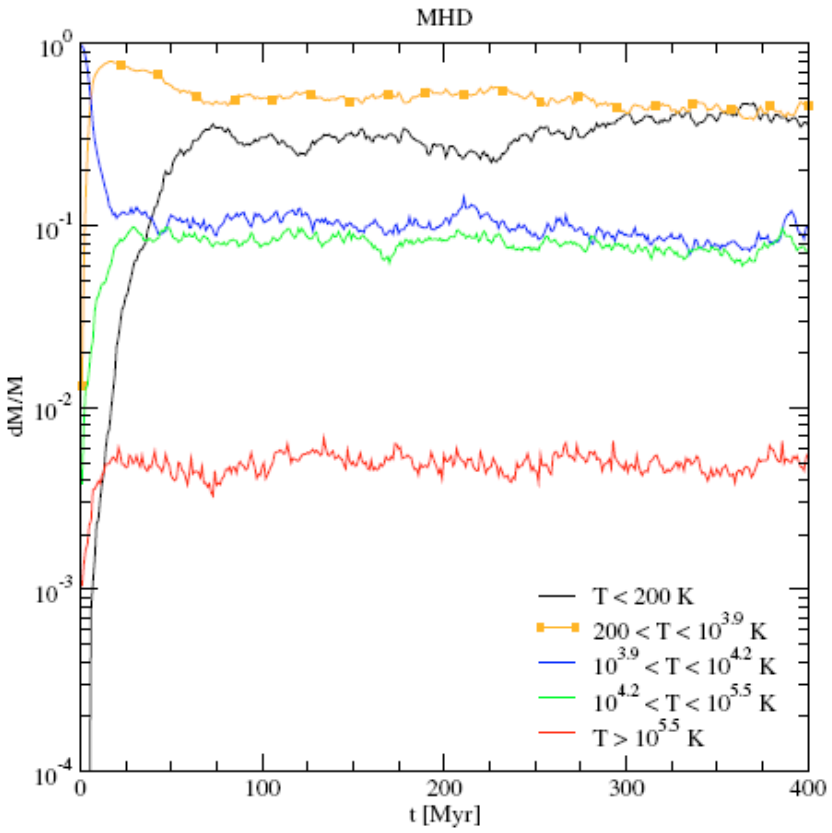


Differential velocity between LISM clouds along same line of sight. Large amplitude scintillating quasars are indicated



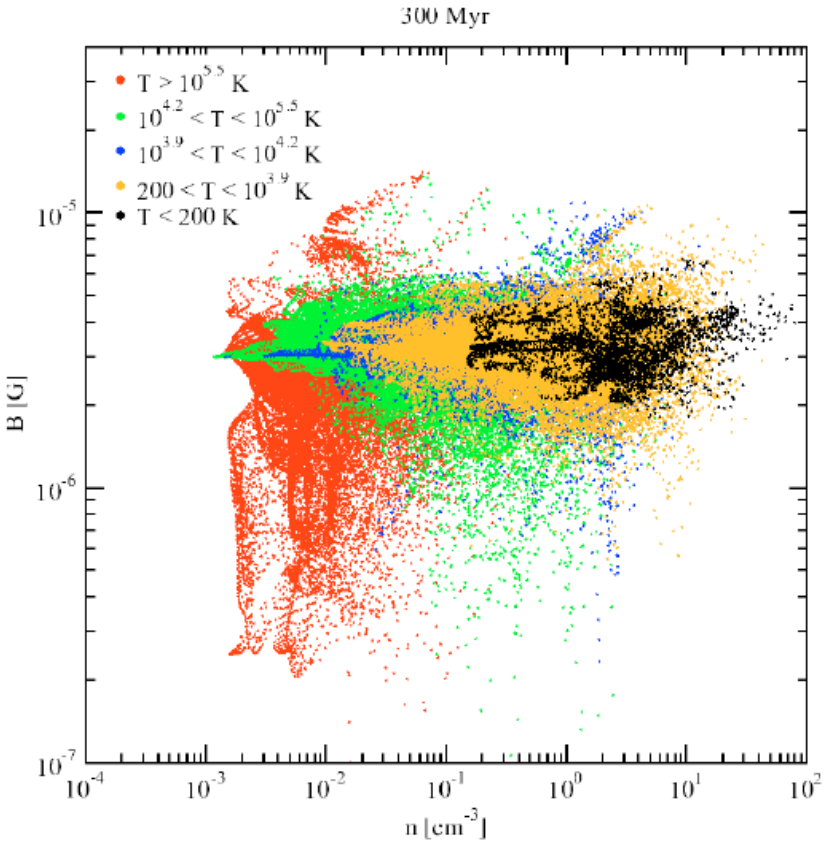
Filling factors by volume (left) and mass (right) (de Avillez & Breitschwerdt A+A 436, 585 (2005))





Magnetic field strength in the 3D MHD models (de Avillez & Breitschwerdt A+A 436, 585 (2005))

- <B> ≈3 μG (initial and at end) but a wide range. Since usually P_{ram}>P_{mag}, the magnetic field is a symptom not a cause of structure in the ISM.
- B is spaghetti-like. B shields warm clouds from thermal conduction.
- Local Bubble is a recombining SB (14.5 Myr old). Last SN 0.5 Myr ago in LB.
- Loop I is an evolving SB.



What are the roles that magnetic fields play in the outer heliosphere and Local Bubble?

(M. Opher, A. Lazarian)

- Magnetic field in the CHISM alters shape of the TS and heliopause. Best fit to TS crossings of V1 and V2 is B=1.8μG at an angle of ~60° relative to Galactic plane. Inclusion of neutrals in models with likely increase magnetic field strength and angle with respect to inflow direction.
- MHD turbulence with high Reynolds number → high intermittancy (extreme events in a small fraction of the volume).

Heliosphere/ISM Interaction Terminology

- Termination shock: where the supersonic solar wind (400-800 km/s) becomes subsonic and heated (94 AU for Voyager 1)
- Heliopause: Interface around the Sun between the subsonic solar wind and ISM plasma (~150 AU)
- Bow shock: where the incoming ISM (26 km/s) becomes subsonic (~250 AU). May not shock depends on magnetic field.
- Hydrogen wall: Pileup of neutral H gas mostly in upwind direction with charge exchange (150-250 AU)
- Plasma models: include electromagnetic and gravity forces on all ionized particles (either as one or multifluid models)
- Kinetic models: treat neutral particles (e.g. H) with long path lengths by Boltzmann equation or Monte Carlo techniques.
- Pickup ions: interstellar neutrals that are ionized (photoionization or charge exchange) and captured by the solar wind magnetic field and accelerated at the termination shock.